European Association for the Development of Renewable Energies, Environment and Power Quality (EA4EPQ)

International Conference on Renewable Energies and Power Quality (ICREPQ'11)
Las Palmas de Gran Canaria (Spain), 13th to 15th April, 2011

Thermal design and analysis of a direct-water-cooled permanent-magnet synchronous generator for high-power direct-drive wind turbine applications

M. Polikarpova, P. Röyttä, S. Semken, J. Nerg and J. Pyrhönen

Department of Electrical Engineering
Lappeenranta University of Technology
Skinnarilankatu 34, 53850 Lappeenranta (Finland)

Phone/Fax number: +358466675242, e-mail: Maria.Polikarpova@lut.fi, Pekka.Röytä@lut.fi, Juha.Pyrhonen@lut.fi, Janne.Nerg@lut.fi

Abstract. As the wind turbines become larger and larger each year, more powerful and reliable generators must be designed for them. The increase of the rated power implies higher current density to achieve the acceptable dimensions for the generator. A direct-water cooling system for the stator winding of the synchronous generator ensures removal of heat losses and therefore safe temperature of the stator winding.

The aim of this paper is determine the performance attributes of the cooling system of the stator winding. The design and evaluation of the cooling system are executed on the basis of analytical calculations and by using Finite Element Method.

Key words

Electrical machines, wind turbine generator, direct-drive, direct water cooling, thermal analysis

1. Introduction

Despite all wind power becomes more and more popular globally as power generation by wind does not need fuel. Wind energy is considered as environmentally friendly and its development is supported by governments. Almost all famous energy technology companies are involved in the race of creating the most reliable, efficient and high power wind generators. The new tendency of the current market is shifting towards the direct drive systems coupled with low-speed permanent magnet synchronous generators (PMSG).

Direct drive PM generators are considered as more reliable than the medium-speed gear based PM generator drives and high-speed induction generators as they are free from the gearbox unreliability. For high power machines (>3 MW) the gearbox becomes more complex and fragile, as it requires an additional stage to the common gearbox and has some temperature problems [8]. Direct drive PMS generators are notable for their high energy yield and low operation and maintenance costs. The gearbox creates about 40 % of the total system losses and it requires routine maintenance during the operation period [2]. However, among the existing generator types the direct drive PMSG is the most expensive one because of the impressive dimensions and weight. As the produced torque is proportional to the square of the air gap diameter the outer radius of the machine should be large for high torque production. This fact causes the main disadvantage of the high-power low-speed gearless PMSG - its large dimensions and big mass that imply high cost.

The problem of impressive dimensions and weight of PMSG can, in principle, be solved by increasing the machine linear current density and the stator winding current density to no less than 8-10 A/mm^2. Such a high current density imposes high ohmic heating within the conductor. It can cause overheating of the copper and damage the winding insulation if specific measures are not used to cool the copper conductor. Also in terms of the permanent magnet rotor, the high temperature heat flux from the stator can cause damage on the permanent magnets' operation as their working temperature is limited to 120-150 $^\circ$C (NdFeB).

The above mentioned problems can be solved through the direct cooling of the stator winding. Despite the existence of the air and hydrogen based solutions for internal cooling of the stator, the direct water based cooling system is the most effective way to remove the heat losses mainly because of high heat capacity of water (4200 J/m^{3}K). However the use of the demineralised water implies additional systems for filtering and cleaning.

The objective of this study is to analyze and evaluate the direct-water cooling system for the stator copper winding of the direct-drive permanent magnet synchronous generator. We have used analytical and Finite Element Method (FEM) based analyses to solve the formulated problems.

2. Description of Thermal Model

A. A Studied Generator

The studied machine is a low-speed, concentrated pole winding, three-phase, rotor-surface-magnet synchronous generator with rated power of 6 MW. The main application of such a generator can be found in wind farms in onshore and offshore applications. The rated speed and torque are 12 rpm and 4.78 MNm respectively. The rated operating frequency is 12 Hz. The low speed and high rated power of the studied generator implies impressive dimensions, as the produced torque is proportional to the square of the air gap diameter. It can be seen from the following equations. As the angular velocity *Ω* and the speed *n* of the machine are low, the torque *T* must be high to achieve a high power *P*.

$$P = \Omega T = 2\pi n T, \qquad (1)$$

he torque can be defined by the next equation based on the utilization of the tangential stress.

$$T = \pi D l \bar{\sigma}_{F\tan} r = \pi \frac{D^2}{4} l \hat{B}_n \hat{A} \cos\varphi, \qquad (2)$$

where D is the diameter of the air gap, l is the stator stack length, σ_{Ftan} is the tangential stress, B_n is the air gap flux density, A is the linear current density, $\cos\varphi$ is the power factor. So a higher torque of the machine can be achieved by increasing the rotor dimensions - air gap diameter or length of rotor. Increasing the air gap diameter and the current density are the best ways, as other parameters are limited by design, operation or physical characteristic of material. For example, an increase of the stator stack length implies a long length of rotor that causes high consumption of permanent magnets, one of the most expensive materials in the machine. The air gap flux density is limited by the properties by the capabilities of permanent magnets. The copper loss in a low speed low frequency machine is the dominating loss component.

$$P_{\mathrm{Cu}} = m R_{\mathrm{AC}} I^{\prime 2}. \qquad (3)$$

Here m is the number of the phases, R_{AC} is the copper AC-resistance, I is the stator current. The total calculated copper losses of the studied 6 MW generator are 623 kW. It is far too high to be removed by the cooling air because of its low heat capacity.

B. Cooling System Introduction

The direct-water cooling system of the stator is designed to remove the heat losses (623 kW) of the stator copper winding and steel frame.

The model of the stator slot is shown as Fig. 1, including stator frame, copper conductors with ducts for water flow, wedge and insulation. Each stator slot presents separate cooling circuit and contains 8 conductors internally. The total number of the cooling circuits is 144. The conductors in slot are joined serially in 4 loops as it shown in Fig.1. This connection was chosen to reduce heat flux in the direction of magnets as their magnetic fields depend strongly on the temperature. The hot heat fluxes can worsen the permanent magnet operation, as their working temperature is limited by 120-150 °C, e.g. in case of NdFeB. The width, height and length of a single copper conductor are 30 mm, 15 mm and 1332 mm respectively.

In order to increase reliability and simplify the cooling system, the water flow velocity assumed to be 1 m/s. This assumption allows reducing the occurrence of the copper tube erosion corrosion.

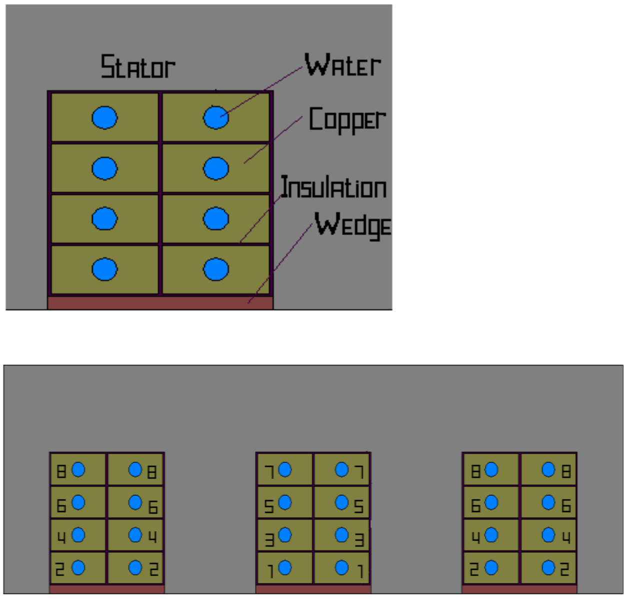


Fig.1. Models of the stator slot (top figure) and connections of conductors in slots (bottom figure) for FEM based analysis.

The erosion of the copper tube can happen if the aerated water flowing internally the copper tube has temperature more than 90 °C and velocity more than 1 m/s. The high velocities in conditions of the high water flow temperatures can cause impingement attack and destruction of the oxide layer formed on the inner copper conductor surface. The assumed low velocity of the cooling water flow helps to avoid the erosion, but it limits the performances of the cooling system.

C. Heat Sources and Thermal Conductivities

In the generator stator the main heat sources are copper losses and iron losses. The copper losses are the biggest one as high electrical currents are generated in the copper winding. The iron losses appeared mainly because of the eddy currents and the hysteresis. The heat generation distributes unevenly among the conductors in the slot because of the skin-effect in copper. The values of heat sources are shown in Table I.

In the model created in FEM based software Flux™, the copper and iron losses are applied as a volumetric heat generation imposed uniformly over the winding volume.

TABLE I. Heat Sources Distribution

Heat Sources Position	
Stator winding (W/m^3)	
- first row (1st and 2nd conductors)	596000
- second row (3 and 4th conductors)	471000
- third row (5 and 6th conductors)	391000
- fourth row (7 and 8th conductors)	352000
-	
Stator yoke (W/m^3)	20600

3. Description of Thermal Model

A. Diameter of Copper Conductor

The direct-water cooling of the stator winding makes a high current density permissible since the heat losses are evacuated efficiently by the cooling water. The high current density allows increasing the output power significantly compared to air cooling, but at the same time it causes a higher resistance of the stator winding. Copper losses become high which result is a lower efficiency. We have used 90% rated efficiency as a boundary conduction as the water cooling is so efficient that even lower efficiencies should be acceptable.

The diameter of the copper conductor hole is determined on the basis of the specified current and the cooling efficiency to ensure an adequate temperature of the copper conductors in the conditions of the high current density. The conductor resistance is inversely proportional to the ratio of the copper cross-section to the hollow area (k_{cw}). To choose a proper value of k_{cw} the contradictory terms should be taken into account. A low k_{cw} implies a low copper cross-section, big losses and low efficiency of the generator. The too high k_{cw} should be avoided from the cooling point of view.

A proper hole of the copper conductor is chosen on the basis of adequate temperature maintenance and little pressure losses along the conductors. The outlet temperature of the cooling water is determined mainly by the inlet temperature of the cooling water and the cross-section of the copper conductor in conditions of the constant heat rate.

$$T_{\mathrm{w}} = T_{\mathrm{wo}} + \frac{P_{\mathrm{Cu}}}{W_{\mathrm{w}} S_{\mathrm{hole}} c_{\mathrm{p}} \rho_{\mathrm{w}}}, \qquad \textbf{(4)}$$

where T_{wo}, T_{w} are the temperatures of inlet and outlet coolant flows, P_{loss} is the heat rate, c_{p} is the heat capacity of the coolant, ρ_{w} is the density of the coolant, S_{hole} is the cross-section of hole and W_{w} is the velocity of the coolant. The temperature to which the copper conductor can be cooled is mainly determined by the convective heat transfer coefficient and the heat exchange surface.

$$T_{\mathrm{s}} = T_{\mathrm{w}} + \frac{P_{\mathrm{Cu}}}{\pi D_{\mathrm{hole}} l_{\mathrm{tot}} h}, \qquad (5)$$

where T_{s} is the temperature of the internal conductor surface, h is the convective heat transfer coefficient between cooling water and the copper conductors, l_{tot} is the total length of the conductors and D_{hole} is the hydraulic diameter of the duct. The convective heat transfer coefficient is determined from the definition of the Nusselt number.

$$Nu \equiv \frac{h \cdot D_{hole}}{k_{\mathrm{w}}}, \qquad (6)$$

where k_{W} is the conductance of the coolant. The correlation proposed by Gnielinski for Nusselt number is used to define its.

$$Nu = \frac{\frac{f}{8} \cdot (\mathrm{Re} - 1000) \cdot \mathrm{Pr}}{1 + 12.7 \cdot \left(\frac{f}{8}\right)^{\frac{1}{2}} \cdot \left(\mathrm{Pr}^{\frac{2}{3}} - 1\right)}, \qquad \textbf{(7)}$$

where f is the friction factor, Re is the Reynolds number and Pr is the Prandtl number. The Reynolds and Prandlt numbers are defined by the next equations

$$\mathrm{Re} \equiv \frac{\rho_{\mathrm{w}} \cdot W_{\mathrm{w}} \cdot D_{\mathrm{hole}}}{\mu_{\mathrm{w}}}, \qquad (8)$$

$$\mathrm{Pr} \equiv \frac{c_{\mathrm{p}} \cdot \mu_{\mathrm{w}}}{k_{\mathrm{w}}}, \qquad \textbf{(9)}$$

where μ_{w} is the dynamic viscosity of the coolant. The friction factor is defined by

$$f = 0.11 \cdot \left(\frac{\varepsilon}{D_{\mathrm{hole}}} + \frac{68}{\mathrm{Re}}\right)^{\frac{1}{4}}, \qquad \textbf{(10)}$$

where ε is the absolute value of average pipe roughness.

Hence, large hydraulic diameter of the conductor hole favours the removing of the generated heat and maintaining an adequate temperature of the copper conductor. At the same time taking into account the efficiency of the generator a proper hole diameter should be the least possible. Figure 2 illustrates the surface temperature of the conductors for different diameters of the conductor hole. As see can be seen in Figure 2 optimal good diameter of the conductor hole is e.g. 7 mm.

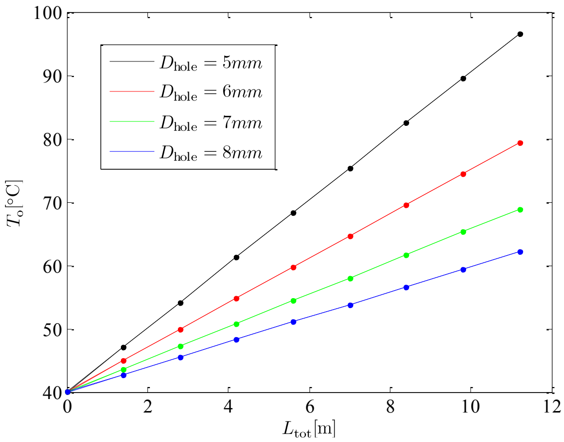


Fig. 2. Surface Temperatures of Conductors with Different Diameters of the Conductor Hole.

The pressure losses along the conductors' junction are the second determined parameter for a proper hole of the copper conductor. Too large pressure losses cause the use of the high power pump that is undesirable. The total pressure losses are determined by the pressure losses along the conductors' length and in the fittings (bends, inlet and outlet of the conductors' junction).

$$\Delta p = (\sum k + \frac{\lambda L}{D_{\mathrm{hole}}}) \frac{\rho_{\mathrm{w}} W_{\mathrm{w}}^{2}}{2}, \quad (11)$$

where Σk is the sum of the resistive coefficients, λ is the friction coefficient. Hence, the pressure losses along the conductors' junction is inversely proportional to the hole diameter. The low velocity of the cooling water flow (1 m/s) is favourable to the reduction of the pressure losses along the conductors' length. Figure 3 presents the pressure losses of water flow in the cooling circuits.

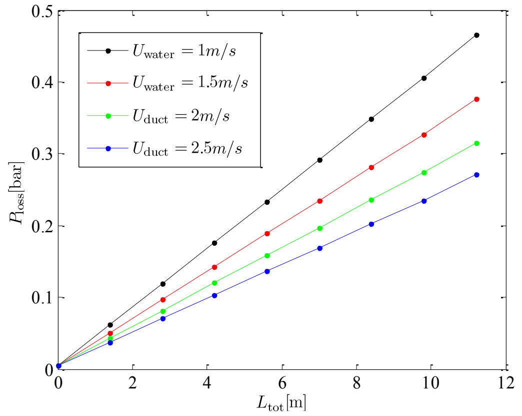
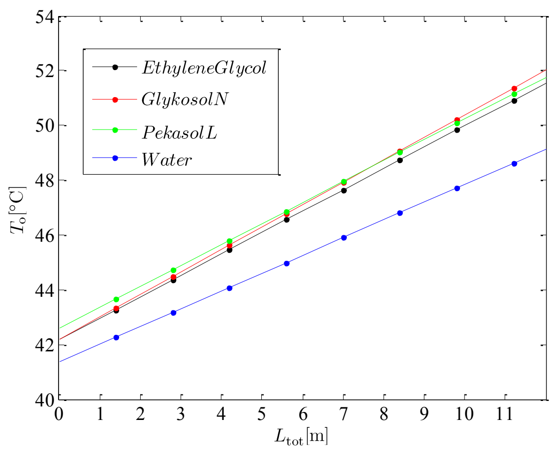


Fig. 3. Pressure Losses of Water Flow along Conductors with Different Diameters of the Conductor Hole.

B. *Coolant for Stator Winding Cooling*

Water is the best coolant in many energy applications, but some limits arise, when it is used as a coolant in the cooling system of stator winding for a wind turbine generator. They are the freezing of water when temperature becomes below 0°C and erosion issues in terms of normal oxygen content and high water flow velocities. The cooling water flow is accepted to have 1 m/s velocity and the outlet temperature less than 90°C to avoid erosion corrosion. The oxygen content of the cooling water can be decreases through special treatment in a deaerator, but this method implies additional systems. The freezing problem can be solved through the mixing of the cooling water with antifreeze additives (chemical treatment).



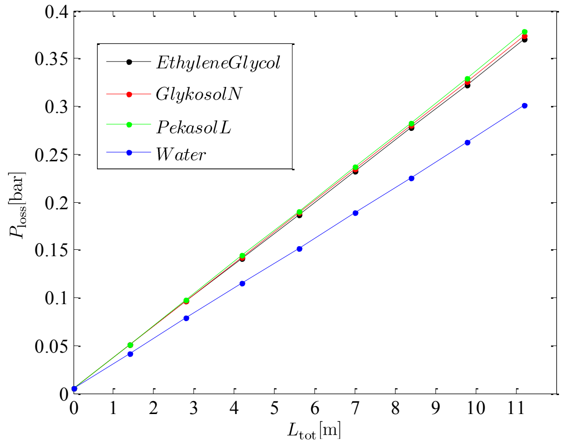


Fig. 4. Surface Temperature of the Conductors along Their Length for Ethylene Glycol, Glykosol N, Pekasol N and Water (top figure).B. Total Pressure Losses along Length of Conductors for Ethylene Glycol, Glykosol N, Pekasol N and Water (bottom figure)

Some solutions of water can be used as coolants to increase the flow velocity and improve the cooling system performance. The above figures 5 and 6 present the comparison of Ethylene Glycol 50 % Vol., Glykosol N 50 % Vol., Pekasol N 50 % Vol. and water as coolants for the direct cooling system of the stator cooper winding. The values of density, thermal conductivity, dynamic viscosity, heat capacity and Prandtl number were taken from Products Technical Data of these fluids [4]-[6]. The characteristics are constructed for 1 m/s velocity of fluid.

The highest erosion rate of copper is in conditions of fluid temperature higher 60°C and little pH values. The presented fluids have 7.5-9 pH and freezing temperature -30°C, but they are inferior to water as coolants due to their higher pressure losses and lower heat capacities. Hence, use of the studied water mixtures is reasonable only if there is a possibility of low temperatures during operation and water cannot remove the generated losses without exceeding the limit of the erosion intensification (1 m/s and 90°C).

4. FEM Based Analysis of Cooling System

A model of the three stator slots was evaluated by 2 D Finite Element Method. As can be seen from Figure 5, the designed cooling system ensures the removal of the generated heat losses. When the heat transfer interactions between the conductors, the tooth and the stator yoke are taken into account, the temperature rise inside the stator becomes lower than it was in the analytical analysis. Figure 6 presents the temperature distribution in axial and radial sections A, B, C, D, E and F of the stator yoke, tooth and conductors. The hottest conductors are the upper ones in slots since they are arranged as outlets in the cooling water flow. The coldest conductors are the ones close to the slot opening which is favourable for magnet reliable operation.

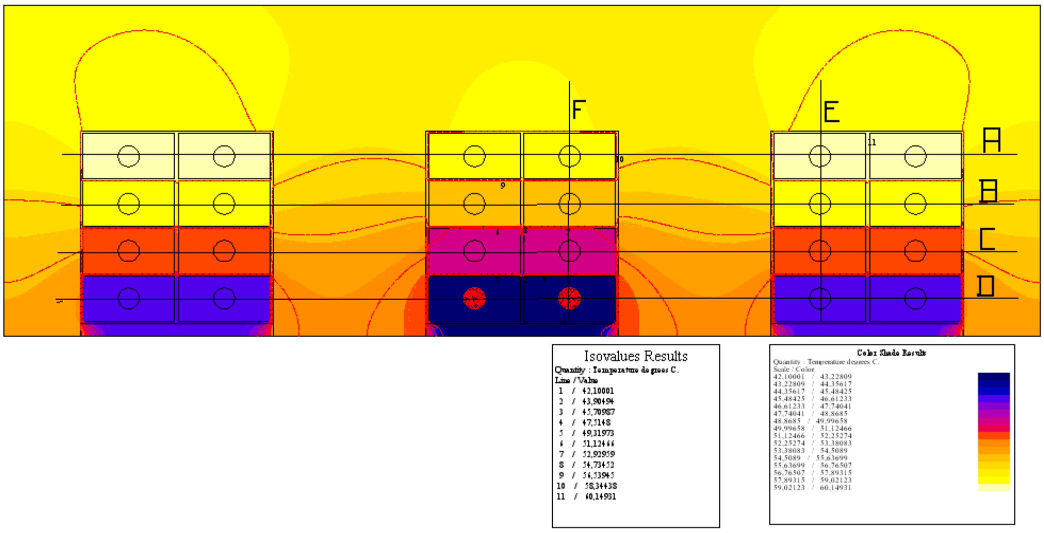


Fig. 5. Temperature distribution inside three stator slots and stator stack.

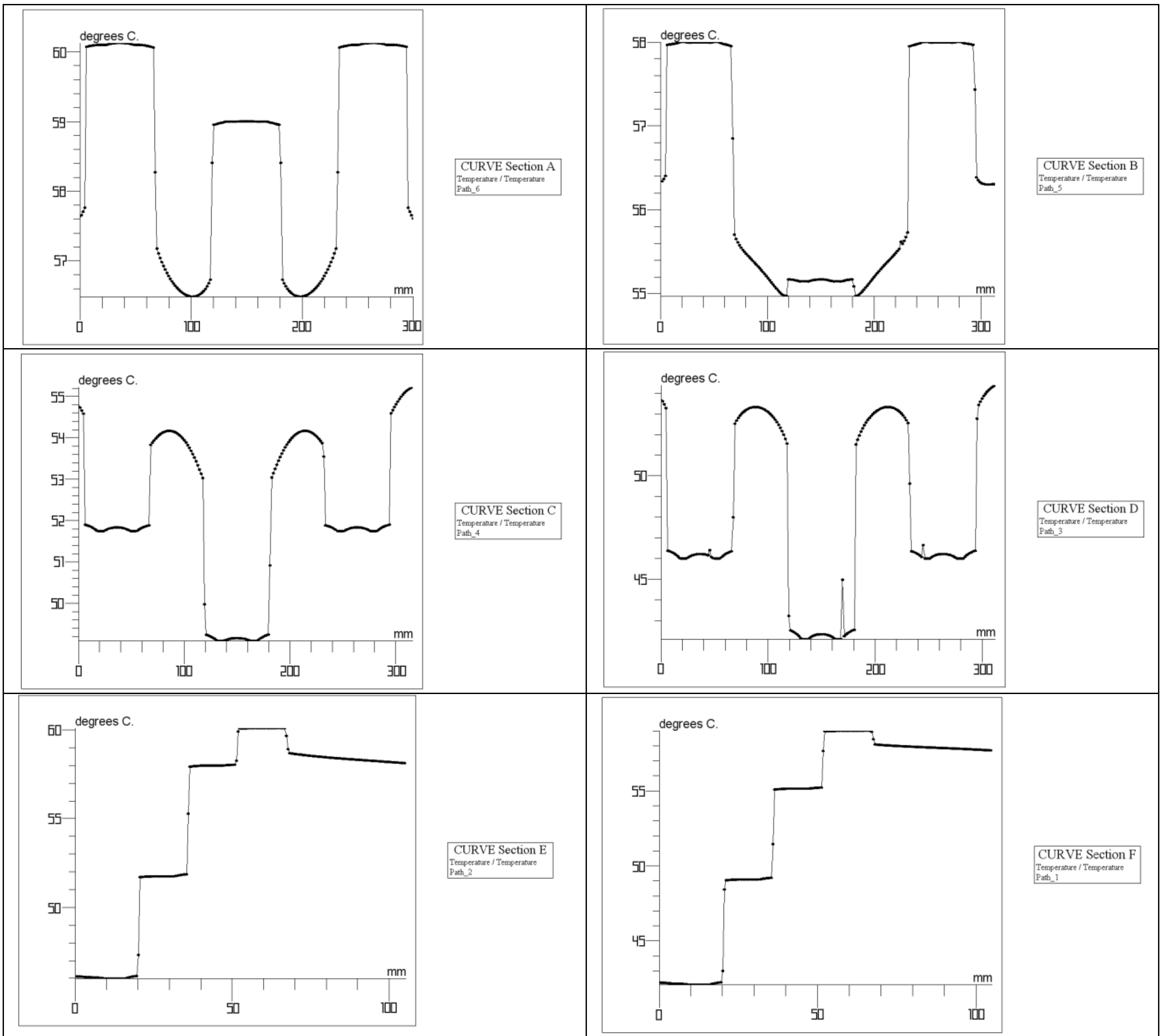


Fig. 6. Temperature Distribution along the Section A (upper left), Section B (upper right), Section D (middle left), Section C (middle right), Section E (lower left), Section F (lower right).

4. Conclusion

DD PMSG is the most reliable and efficient among the presented high power generators presented on the market. Internal water cooling system allows solving the main problem of these generators - tremendous dimensions. As can be seen in the paper direct-water cooling is shown to be a highly efficient method to remove heat losses (623 kW).

Internal water cooling of stator winding ensures quite uniform and adequate temperature of the conductors. It favours safe operation of permanent magnets since water removes copper losses totally. In case of low working temperatures, different water solutions can be used as a coolant. The studied Ethylene Glycol 50% Vol., Glykosol N 50% Vol., Pekasol N 50% Vol. are slightly worse than water from the cooling point of view.

References

[1] F. P. Incropera, D.P. Dewitt, T.L. Bergman and A.S.Lavine, Fundamentals of Heat and Mass Transfer, 6th edition. USA, John Wiley&Sons pub. (2007), pp. 320-440.

[2] S.V. Patankar, Numerical heat transfer and fluid flow. New York: Hemisphere pub., 1980, pp. 41-77.

[3] D.-j. Bang, H. P. Under, G. Shrestha, and J. Ferreira, "Promising direct-drive generator system for large wind turbines," in *Wind Power to the Grid Seminar (EPE-WECS 2008)*, 2008.

[4] Product Technical Data 'Pekasol L', pro KUHLSOLE GmbH, Alsdorf, Germany, January 2001. Available: hptt://www.prokuehlsole.de

[5] Product Technical Data 'Glykosol N', pro KUHLSOLE GmbH, Alsdorf, Germany, January 2001. Available: hptt://www.prokuehlsole.de

[6] Product Technical Data 'Thermophysical Properties of Brines', M. Code Engineering, Zurich, Switzerland, 2002. Available: hptt://www.mrc-eng.com

[7] Dewitt, "Offshore wind energy: Ready to power a sustainable Europe, concerted action on offshore wind energy in Europe", Final Report NNE5-1999-562, Supported by the European Commession, Dec.2001.